N89-10741

PRECEDING PAGE BLANK NOT FILMED

ROTATIONAL MODULATION OF HYDROGEN LYMAN ALPHA FLUX FROM 44i BOOTIS*

O. VILHU[1], J.E. NEFF[2], and T. RAHUNEN[3]

[1]Observatory, University of Helsinki, SF-00130 Helsinki, Finland
[2]JILA, University of Colorado, Boulder, CO 80309-0440, USA
[3]Sarkanniemi Oy, Tampere, Finland

* Based on observations with the International Ultraviolet Explorer (IUE) obtained at the Villafranca satellite tracking station of the European Space Agency and at NASA/GoddardSpace Flight Center.

ABSTRACT

We present IUE observations that cover the entire 6.4 hour orbital cycle of the late-type contact binary 44i Bootis. The intrinsic stellar hydrogen Lyman alpha emission flux was determined from low-resolution IUE spectra, compensating for geocoronal emission and for interstellar absorption. The variation of the stellar Lyman alpha emission flux correlates well with the variation of the CII and CIV emission fluxes, and it shows orbital modulation in phase with the visual light curve. The ratio of Lyman alpha to CII flux (15 to 20) is similar to that observed in solar active regions. Hydrogen Lyman alpha emission is thus one of the most important cooling channels in the outer atmosphere of 44i Boo. We obtained a high-resolution spectrum of the Lyman alpha line between orbital phases 0.0 and 0.6. The integrated flux in the observed high-resolution Lyman alpha profile is consistent with the fluxes determined using low-resolution spectra, and the composite profile indicates that both components of this binary have equally active chromospheres and transition regions. The uncertainty in the interstellar hydrogen column density cannot mimic the observed variation in the integrated Lyman alpha flux, because the stellar line is very much broader than the interstellar absorption.

Key Words: magnetic activity-chromospheres-Lyman alpha emission- ultraviolet spectroscopy - contact binaries

1. INTRODUCTION

The atmospheres of late-type stars consist of relatively cool photospheres, warm chromospheres, and hot coronae. The chromosphere and corona are separated by a thin transition region, in which the temperature changes abruptly from about 7000 K to several million K.

The Lyman alpha line at 1216 Angstroms plays a crucial role in the energetic relationship between the chromospheres and coronae of cool stars. Unfortunately, the possible correlation between the the Lyman alpha line flux and other chromospheric and transition region line fluxes has not yet been investigated, mainly because the very strong Lyman alpha line is generally overexposed on all IUE SWP spectra taken with exposure times long enough to make other interesting spectral features, such as CIV 1550 and CII 1335, visible. In addition, the stellar emission in low-resolution spectra is severely contaminated by scattered solar Lyman alpha emission from the geocoronal environment of the IUE satellite. Further, interstellar absorption can remove a significant fraction of the intrinsic stellar flux from the line.

Nearby contact binaries are good targets to study the Lyman alpha emission, because they are expected to have strong emission and because their emission lines are rotationally broaded so that interstellar absorption does not remove a large fraction of the total flux. In addition, the short periods of contact binaries allow an orbital modulation study to be made. It is possible to perform a simultaneous study of the Lyman alpha line and many chromospheric and transition region emission lines from the contact binary system 44i Bootis with short SWP exposures (which would not be saturated at Lyman alpha). In addition, 44i Boo is bright enough that a high resolution Lyman alpha spectrum can be obtained (although over a large spread in orbital phases), allowing an important check on the techniques used to remove the effects of geocoronal emission and interstellar absorption from the low-resolution spectra.

2. OBSERVATIONS AND CORRECTION FOR THE GEOCORONAL EMISSION AND INTERSTELLAR ABSORPTION

44i Bootis (HD 133640; SAO 45357) is a contact binary at a distance of 12 pc. It has been well studied with the IUE (Rucinski and Vilhu 1983) and with the EINSTEIN (Cruddace and Dupree 1984) and EXOSAT (Vilhu and Heise 1986) observatories.

The amplitudes of the radial velocity variations are K1=115 km s^{-1} and K2=231 km s^{-1} (Batten, Fletcher, and Mann 1978). The mass ratio is M2/M1=0.50, and the orbital inclination i=77° (Rucinski 1973). The ephemeris of light minimum given in Vilhu and Heise (1986) needs to be corrected by 0.015 days to be consistent with the July 1986 photometry of Al-Naimiy et al. (1986). We used the orbital ephemeris JD(min)=2439852.5053 and an orbital period of 0.2678159 days.

The low-resolution SWP observations were performed on 28 June 1986 during a contiguous US2+ESA double shift (16 hours), covering roughly one orbital cycle. A high-resolution spectrum was obtained on 6 July 1986, with an exposure begun at about primary minimum lasting until secondary minimum (one half of the orbital cycle).

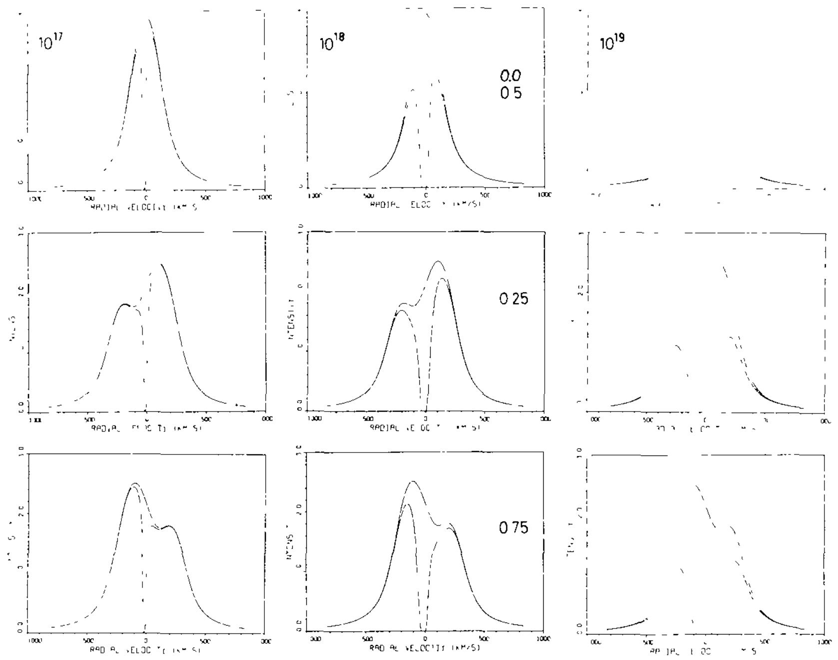

Fig. 1 Model profiles for the Lyman alpha emission line for 44i Boo. The models include the rotational and intrinsic broadening of both components and the absorption due to interstellar hydrogen. Models were computed for three hydrogen column densities (10^{17}, 10^{18}, and 10^{19} atoms cm^{-2}) and for three orbital phases. The intensity scale is arbitrary, and wavelength (horizontal) scale (km s^{-1}) has its origin at the binary's center of mass.

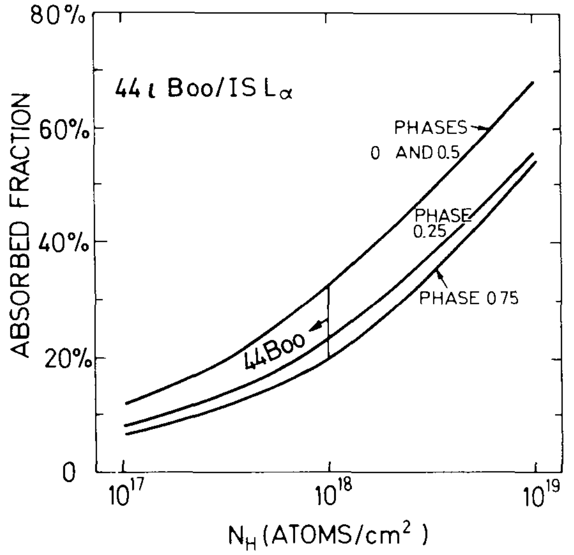

Fig. 2 The fraction of stellar Lyman alpha emission that is absorbed as a function of the hydrogen column density and orbital phase.

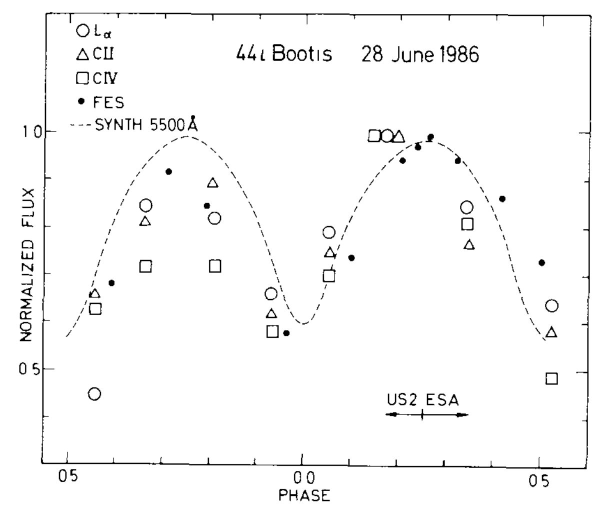

Fig. 3 The stellar Lyman alpha, CII 1335, and CIV 1550 emission line light curves of 44i Boo. The visual points from the IUE Fine Error Sensor (FES) and the computed synthetic visual light curve (SYNTH) are marked.

All reduction and analysis of the IUE observations was performed using software at the Colorado Regional Data Analysis Facility (RDAF). After applying the standard flux calibration to the one-dimensional extracted spectra, the Lyman alpha, CII (1335 Angstroms), and CIV (1550 Angstroms) were determined by fitting a gaussian emission profile to the spectral line and a quadratic function to the local background.

Solar Lyman alpha emission is resonantly scattered into the line of sight by hydrogen in the "geocorona". The major axis of the elliptical large aperture is oriented roughly perpendicular to the dispersion in low-resolution spectra and roughly parallel to it in high-resolution spectra. From the geosynchronous orbital position of the IUE spacecraft, geocoronal emission is seen from all directions, therefore uniformly illuminating the aperture. The intensity of the two-dimensional (spatial and spectral dimensions) geocoronal profile varies with the angle between the line of sight and the sun (the Beta angle), the angle between the line of sight and the Earth, and the intrinsic variability of the solar Lyman alpha (Clarke 1982), but the shape of the profile is due solely to instrumental factors. This profile shows light loss near the edge of the aperture due to the point-spread function of the telescope and is rougly flat across the center of the aperture.

We subtracted the geocoronal profile from the low-resolution SWP images using the method developed by Neff et al (1986). The correction procedure operates on the standard line-by-line (ELBL) files, which include a series of spatially resolved spectra. These spatially resolved spectra are treated as an "image" of the aperture. Geocoronal emission is present throughout the aperture, while the stellar emission is confined to the center of the aperture. We fitted a model profile perpendicular to the dispersion (i.e. in the spatial dimension) at each wavelength within the aperture. This profile was subtracted from each spatial slice to produce a corrected line-by-line file, which may then be co-added with standard IUE software to yield the stellar spectrum with the geocoronal background removed.

The geocoronal model profile consists of gaussian wings fit to the outer portion of the aperture (where light loss is significant) and a linear interpolation across the center of the aperture (the central 11 lines in the line-by-line spectrum). We therefore use the information within the aperture but outside the region that contains stellar emission to determine the intensity level of the geocoronal emission. Thus, this procedure will work with any spectrum in the IUE archives. This profile has proven to give a satisfactory fit in cases when only the geocorona was observed (sky background or quasar spectra, Neff et al. 1986). For this particular set of observations the stellar emission was strong and exposure times short, so the geocoronal contribution was relatively small.

Because the Lyman alpha line profile is not resolved in low-resolution observations, the only way to estimate how much of the stellar flux is removed by interstellar absorption is to model both the stellar emission and interstellar absorption profiles. The only observational constraint available in the low-resolution spectra is the total integrated flux in the earth-received profile. Other parameters of the model must be constrained with prior knowledge or else varied between their reasonable limits. We used the method described by Rucinski, Vilhu, and Whelan (1985), who argued that since the stellar profiles of contact binaries are very broad (rapid rotators), the interstellar absorption is not extremely large unless the interstellar hydrogen column density is greater than 10^{19} cm^{-2}. For narrow-lined stars the situation is quite different, as even very small column densities cause the interstellar absorption to affect the entire stellar emission profile.

Figure 1 shows a set of theoretical Lyman alpha emission line profiles for 44i Boo computed with the code kindly provided by Dr S.M. Rucinski. This code was described by Rucinski, Vilhu, and Whelan (1985) in their similar study of W UMa. For 44i Boo we used the mass ratio 0.5, the orbital inclination 77 degrees, and the contact fill-out factor 0.9 (as given in Rucinski 1973). We used different interstellar hydrogen column densities, although the most probable value is less than 10^{18} cm^{-2} (Vilhu and Heise 1986).

The system radial velocity of 44i Bootis, with respect to the sun, is 3.4 km s^{-1} (Batten, Fletcher, and Mann 1978). The long astrometric orbit does not affect this value significantly. Using the flow vector for the local interstellar medium (l,b,v)=(25°,10°,-28 km s^{-1}) from Crutcher (1982), the radial velocity of the interstellar gas in the direction of 44 i Bootis is -12.6 km s^{-1}. In this way we deduce that the interstellar gas is moving with respect to 44i Boo with a velocity of approximately -16 km s^{-1}. This value was used in modelling the interstellar absorption.

Figure 2 shows the fraction of the total stellar Lyman alpha emission flux that is absorbed as a function of the interstellar hydrogen column density and orbital phase. Typically, when N(H) is less than 10^{18} cm^{-2}, the absorbed fraction is less than 25%, and it varies with the orbital phase by less than 10%.

3. RESULTS

Figure 3 shows the light curves for the Lyman alpha, CII 1335, and CIV 1550 emission lines, normalized to their maximum values. The Lyman alpha fluxes were corrected for geocoronal emission and for interstellar absorption (assuming N(H)=10^{18} cm^{-2}). The FES counts (representing the V light curve) are plotted together with a synthetic visual (5500 Angstroms) light curve computed with the code kindly provided by Dr. S. M. Rucinski. This code was described by Rucinski (1973). Between orbital phases 0.0 and 0.5 the emission line and visual light curves are very similar (f/f(bol)=constant). However, the line fluxes (especially CIV) seem to be lower between the phases 0.5 and 0.0. If true, this indicates that the transition region on the phase 0.75 side of the system is fainter than that on the phase 0.25 side. However, these observations were made at higher radiation levels and are of poorer quality than those observed later, when the radiation was negligible.

The high-resolution spectrum SWP28625 obtained about a week later between phases 0 and 0.5 provides us with a means to verify our Lyman alpha correction procedures. The spectrum is shown in Figure 4. In this high-resolution spectrum the narrow geocoronal emission is clearly seen, mostly masking the underlying interstellar absorption. However, the broad stellar wings are visible. For comparison, a theoretical profile is shown. This profile was computed with N(H)=10^{18} cm^{-2} and a flux mean between phases 0.92 and 0.57, weighting the profiles of different phases with the low-resolution Lyman alpha fluxes (after the geocoronal subtraction). The total flux in the theoretical stellar emission profile (without interstellar absorption) is 17.2 10^{-12} erg s^{-1} cm^{-2}. This value is somewhat uncertain (+/-20%), since no actual fit with the observed wings was attempted. However, the fit is reasonable, and the total Lyman alpha flux used is quite compatible with the mean low-resolution flux between phases 0 and 0.5.

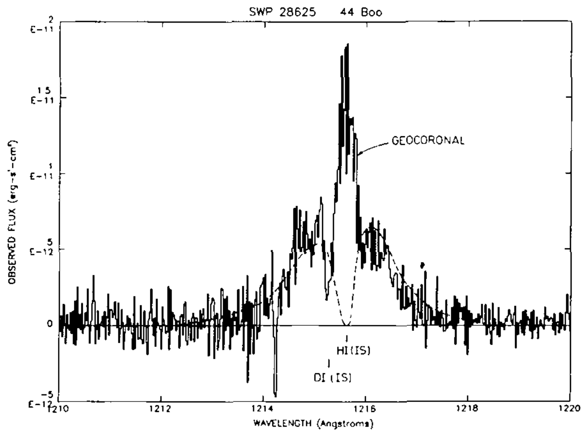

Fig. 4 The high-resolution Lyman alpha spectrum of 44i Boo obtained 6 July 1986, between orbital phases 0.92-0.57. The theoretical profile is shown by the dashed line. The geocoronal emission is clearly visible inside the broad stellar emission wings. The positions of the interstellar neutral hydrogen and deuterium are marked.

4. DISCUSSION AND SUMMARY

The symmetry of the high-resolution Lyman alpha profile and the lack of any clear rotational modulation of the line fluxes imply that both components of the 44 i Bootis system must have similar chromospheres and transition regions. This should be expected, because both components have almost equal effective temperatures and apparently equal angular velocities. To a zeroth approximation, each component would therefore have equal "dynamo numbers".

The classical theory of contact binaries assumes "a common convective envelope" where both stars are embedded. However, more developed theories deviate from thermal equilibrium, producing quite unequal convective zones for the component stars (see for example Rahunen 1981 and 1982; Rahunen and Vilhu 1982). If the chromospheric and transition region line fluxes are indicative of the magnetic activity, then the dymamo power of the components should be equal, and the physical properties of the dymamo layers (such as temperature, density, rotation, differential rotation, turbulent velocities, etc.) shoul be equal as a consequence. However, as pointed by Vilhu and Heise (1986), because contact binaries are close to the observed saturation limits of all chromospheric and transition region indicators, this test is very insensitive to the dynamo-related parameters.

The total CII and Lyman alpha intensities of solar active regions are correlated, and a linear relation F(Lyman alpha) = 25F(CII) for a sample of active regions follows from Schrijver et al. (1986). We find for 44i Boo F(Lyman alpha) = (18 +/- 6)F(CII), quite consistent with the solar active region data. We note, however, that the absolute values of the surface fluxes in 44i Boo are much larger, indicating higher surface coverage of magnetic field than in solar plages. In the most intense solar active region studied by Schrijver et al. F(Lyman alpha) = 2.5E6 erg s^{-1} cm^{-2}, compared with the mean value 6.5E6 erg s^{-1} cm^{-2} for 44i Boo.

ACKNOWLEDGEMENTS

We are very grateful to Slavek Rucinski for providing us with his contact binary computer codes. This work was supported by NASA grant NAG5-82 to the University of Colorado. The data analysis was performed at the Colorado Regional Data Analysis Facility, which is supported by NASA grant NAG5-26409 to the University of Colorado.

REFERENCES

Al-Naimiy et al. 1986 (IBVS 2956).
Batten, A.H., Fletcher, J.M., Mann, P. 1978, Publ. Dominion Astrophys. Obs. XV, No. 5.
Clarke J.T. 1982, ApJ, 263, L105.
Cruddace, R.G., Dupree, A.K. 1984, ApJ, 277, 263.
Crutcher, R.M. 1982, ApJ, 254, 82.
Neff J.E., Linsky J.L., Landsman W.B., Carpenter K.G. 1986, in "New Insights in Astrophysics: 8 Years of UV Astronomy with IUE", ESA-SP263, p. 669.
Rahunen, T. 1981, Astron. Astrophys., 102, 81.
Rahunen, T. 1982, Astron. Astrophys., 109, 66.
Rahunen, T., Vilhu, O. 1982, in "Binary and Multiple Stars as Tracers of Stellar Evolution", eds. Z. Kopal and J. Rahe, Reidel:Dordrecht, p. 289.
Rucinski, S.M. 1973, Acta Astr., 23, 79.
Rucinski, S.M., Vilhu, O. 1983, M.N.R.A.S., 202, 1221.
Rucinski, S.M., Vilhu, O., Whelan, J.A.J. 1985, Astron. Astrophys., 143, 153.
Vilhu, O., Heise, J. 1986, ApJ, 311, 937.